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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicants: Jonathan J. Wierer, Jr.; Michael R. Krames; Serge L. Rudaz
 Assignee: Lumileds Lighting U.S. LLC
 Title: Multi-Layer Highly Reflective Ohmic Contacts For Semiconductor Devices
 Serial No.: 09/469,652 Filing Date: December 22, 1999
 Examiner: Jerome Jackson Group Art Unit: 2815
 Docket No.: M-9197 US

San Jose, California

Commissioner for Patents
 P. O. Box 1450
 Alexandria, VA 22313-1450

DECLARATION OF JONATHAN J. WIERER JR.

Dear Sir:

Jonathan J. Wierer Jr. declares as follows:

1. I received my Bachelor's, Master's, and Ph. D. degrees in Electrical Engineering from the University of Illinois in 1994, 1995, and 1999. I have worked in the field of semiconductor devices for 11 years. I am a co-inventor of the above-referenced patent application.
2. I have calculated the p-contact resistance for the device described in P.M. Mensz, P. Kellawon, R. van Roijen, P. Kozodoy, and S. Denbaars, *In_xGa_{1-x}N/Al_yGa_{1-y}N violet light emitting diodes with reflective p-contacts for high singled sided light extraction*, Electronics Letters 20th November 1997 Vol. 33 No. 24, pp.2066-2068 (hereinafter "Menz").
3. The attached Figure 1 gives a circuit diagram for a semiconductor light emitting diode, such as the device of Mensz. The circuit includes the resistance of the p-contact $R_{p\text{-contact}}$, the resistance of the p-type region $R_{p\text{-semiconductor}}$, the voltage necessary to

PATENT LAW
 GROUP LLP
 2535 N. FIRST ST.
 SUITE 225
 SAN JOSE, CA 95134
 (408) 352-0480
 FAX (408) 352-0481

pass current through the p-n junction V_{gap} , the resistance of the n-type region $R_{n-semiconductor}$, and the n-contact resistance $R_{n-contact}$. $R_{p-contact}$ may be rewritten in terms of the contact resistance $\rho_{p-contact}$, which is a function of the contact material, and the area of the p-contact $A_{p-contact}$ as given by equation (1):

$$R_{p-contact} = \frac{\rho_{p-contact}}{A_{p-contact}} \quad (1)$$

4. The forward voltage V_f of the device at driving current I is given by equation (2):

$$V_f = (R_{p-contact} + R_{p-semiconductor} + R_{n-semiconductor} + R_{n-contact})I + V_{gap} \quad (2)$$

5. From equations 1 and 2, an expression for contact resistance $\rho_{p-contact}$ may be derived, as given by equation (3):

$$\rho_{p-contact} = \left(\left(\frac{V_f - V_{gap}}{I} \right) - (R_{p-semiconductor} + R_{n-contact} + R_{n-semiconductor}) \right) A_{p-contact} \quad (3)$$

The values for V_f , I , and $A_{p-contact}$ are shown in paragraph 6, the value $R_{p-semiconductor}$ is calculated in paragraph 7, the value of $R_{n-contact}$ is calculated in paragraph 8, and the value of $R_{n-semiconductor}$ is calculated in paragraph 9, and the value of V_{gap} is calculated in paragraph 10. In paragraph 11, the values are substituted in equation 3 and the p-contact resistance is calculated. All values are calculated in favor of Mensz to give the lowest possible $\rho_{p-contact}$.

6. At page 2067, column 2, line 24 of Mensz, the value for current I is given as 20 mA, or 0.20 A. At page 2067, column 2, line 34 of Mensz, the value for forward voltage V_f is given as 5.0 ± 0.1 V. At page 2067, column 1, line 36 of Mensz, the value for area of the p-contact $A_{p-contact}$ is given as $300 \times 300 \mu m^2$, or $0.0009 cm^2$.

7. The resistance $R_{p-semiconductor}$ is given by equation 4:

$$R_{p-semiconductor} = \frac{\rho_{p-sheet} L}{A_{p-contact}} \quad (4)$$

where $\rho_{p\text{-sheet}}$ is the sheet resistance of the p-type semiconductor, L is the thickness of the p-type semiconductor, and $A_{p\text{-contact}}$ is the area of the p-contact. At page 2067, column 1, lines 29-33, Mensz recites several p-type layers, including: "p-type GaN doped with Magnesium at $1 \times 10^{19} \text{ cm}^{-3}$. . . Mg doped layers of 150Å thick p-Al_{0.10}Ga_{0.90}N doped at $1 \times 10^{19} \text{ cm}^{-3}$, 600Å thick graded composition p-Al_yGa_{1-y}N, from $y = 0.10$ to $y = 0.0$, doped at $5 \times 10^{19} \text{ cm}^{-3}$, and 2000Å thick p⁺-GaN doped at $1 \times 10^{20} \text{ cm}^{-3}$ " Adding all of these layers gives a total p-layer thickness of 2750Å or 0.0000275 cm. The sheet resistance $\rho_{p\text{-sheet}}$ of GaN is reported by S. Nakamura, Semiconductors and Semimetals, Vol. 48, 391 (1997) to be between 2 and 8 Ω-cm. Since the higher value of sheet resistance $\rho_{p\text{-sheet}}$ gives a smaller value for contact resistance $\rho_{p\text{-contact}}$, the value of 8 Ω-cm is used. As described above in paragraph 8, the area of the p-contact $A_{p\text{-contact}}$ is 0.0009 cm². Substituting these values in equation 4 as illustrated below gives a value of $R_{p\text{-semiconductor}}$ of 0.18 Ω.

$$R_{p\text{-semiconductor}} = \frac{(8\Omega\text{cm})(0.0000275\text{cm})}{0.0009\text{cm}^2} = 0.24\Omega \quad (4)$$

8. The resistance $R_{n\text{-contact}}$ is given by equation 5:

$$R_{n\text{-contact}} = \frac{\rho_{n\text{-contact}}}{A_{n\text{-contact}}} \quad (5)$$

where $\rho_{n\text{-contact}}$ is the n-contact resistance and $A_{n\text{-contact}}$ is the area of the n-contact. Mensz states at page 2067, column 1, lines 39 and 40 that the n-contact is Ti/Al. The n-contact resistance of Ti/Al on n-type GaN is reported by Lin et al., Low resistance ohmic contacts on wide band-gap GaN, Appl Phys. Lett. 64 (8) (1994) to be between $3 \times 10^{-3} \Omega\text{-cm}^2$ for a small contact area and $8 \times 10^{-6} \Omega\text{-cm}^2$ for a large contact area. Without knowing the exact quality of Mensz's n-contact, $3 \times 10^{-3} \Omega\text{-cm}^2$ is used for the n-contact resistance. This gives the highest $R_{n\text{-contact}}$ (and hence the lowest $\rho_{p\text{-contact}}$). The contact area is assumed to be the $100 \times 100 \mu\text{m}^2$ or $0.01 \times 0.01 \text{ cm}^2$. This is the smallest contact area that can be probed and wire-bonded, and was chosen because using a small contact area increases the size of the $R_{n\text{-contact}}$ term, which

decreases the $\rho_{p\text{-contact}}$. Substituting the values for n-contact resistance $\rho_{n\text{-contact}}$ and n-contact area $A_{n\text{-contact}}$ in equation 5 as illustrated below gives a value for $R_{n\text{-contact}}$ of 30 Ω .

$$R_{n\text{-contact}} = \frac{3 \times 10^{-3} \Omega \text{cm}^2}{(0.01 \text{cm})(0.01 \text{cm})} = 30 \Omega \quad (5)$$

9. The resistance $R_{n\text{-semiconductor}}$ is given by equation 6:

$$R_{n\text{-semiconductor}} = \frac{L}{A_{n\text{-semiconductor}} q n \mu} \quad (6)$$

where L is the length current must spread in the n-type layer, $A_{n\text{-semiconductor}}$ is the cross sectional area through which current must spread, q is the electron charge, n is the electron concentration in the n-type layer, and μ is the mobility of the electrons in the n-type layer. For a square $300 \times 300 \mu\text{m}^2$ p-contact, the size recited by Mensz at page 2067, column 1, line 36, the average current spreading length L is assumed to be 150 μm , or 0.015 cm. The cross-sectional area $A_{n\text{-semiconductor}}$ is 300 μm (the length of one side of the p-contact) times the thickness of n-type material through which current must spread. At page 2067, column 1, lines 22-26, Mensz teaches three n-type layers: "2.5 μm of n-type GaN doped with Si at $2 \times 10^{18} \text{ cm}^{-3}$ donor concentration . . . a 450 Å thick graded composition layer of n- $\text{Al}_y\text{Ga}_{1-y}\text{N}$ from $y = 0$ to $y = 0.08$, and a 150 Å thick n- $\text{Al}_{0.08}\text{Ga}_{0.92}\text{N}$ layer . . . both doped with Si at $1 \times 10^{18} \text{ cm}^{-3}$." Since the 450 Å thick graded layer and the 150 Å thick AlGaIn layer add only negligibly to the resistance, the thickness of n-type material through which current must spread is assumed to be 2.5 μm , or 0.00025 cm. The electron charge q is $1.6 \times 10^{-19} \text{ C}$. Mensz recites a donor or electron concentration n of $2 \times 10^{18} \text{ cm}^{-3}$ in the above-quoted passage. The electron mobility in n-GaN is reported by Götz et al., Activation energies of Si donors in GaN, Appl. Phys. Lett. 68 (22) (1996) to be $300 \text{ cm}^2/\text{Vs}$. Substituting these values in equation 6 as illustrated below gives a value of $R_{n\text{-semiconductor}}$ of 20.8 Ω .

$$R_{n\text{-semiconductor}} = \frac{0.015 \text{cm}}{(0.03 \text{cm})(0.00025 \text{cm})(1.6 \times 10^{-19} \text{C})(2 \times 10^{18} \text{cm}^{-3})(300 \text{cm}^2/\text{Vs})} = 20.8 \Omega \quad (6)$$

10. The voltage V_{gap} is given by equation 7:

$$V_{gap} = \frac{hc}{\lambda} \quad (7)$$

where h is Planck's constant, 4.14×10^{-15} V.s, c is the speed of light in a vacuum, 3×10^8 m/s, and λ is the wavelength of light, stated at page 2067, column 2, line 12 to be 412 nm or 412×10^{-9} m. Substituting these values in equation 7 as illustrated below gives a V_{gap} of 3V.

$$V_{gap} = \frac{(4.14 \times 10^{-15} \text{ V} \cdot \text{s})(3 \times 10^8 \text{ m/s})}{(412 \times 10^{-9} \text{ m})} = 3 \text{ V} \quad (7)$$

11. The values in paragraphs 6-10 are substituted in equation 3 as illustrated below:

$$\rho_{p\text{-contact}} = \left(\left(\frac{5V - 3V}{0.02A} \right) - (0.24\Omega + 30\Omega + 20.8\Omega) \right) 0.0009 \text{ cm}^2 = 0.044 \Omega\text{-cm}^2 \quad (3)$$

Since all the assumptions made in the above calculations favor arriving at the lowest possible $\rho_{p\text{-contact}}$, I believe $0.044 \Omega\text{-cm}^2$ is the lowest possible $\rho_{p\text{-contact}}$ for Mensz's device.

I declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the above-referenced application or any patent issued therefrom.

Signed:

Date:

Justin J. Winn Jr.
30 June 2005

PATENT LAW
GROUP LLP
25M N. FIRST ST.
SUITE 200
SAN JOSE, CA 95124
(408) 383-0481
FAX (408) 383-0481